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## $n+p\to d+\gamma$ AND TIME-REVERSAL INVARIANCE*

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Measurements are reported of the differential and total cross section for $n+p\to d+\gamma$ for neutron energies between 160 and 640 MeV. A comparison is made with the differential and total cross sections for the inverse process.

We have measured the angular distribution and the total cross section for the reaction

$$n+p\to d+\gamma. \quad (1)$$

Results have been obtained for four intervals of neutron laboratory energy between 160 and 640 MeV. This study was prompted by the suggestion that time-reversal invariance may not be valid for the electromagnetic interaction of the hadrons.[1,2] A failure of time-reversal invariance could lead to a difference between the center-of-mass angular distribution of the deuteron in Reaction (1) and that of the proton in the inverse reaction

$$\gamma+d\to n+p. \quad (2)$$

To be sensitive, the comparison of angular distributions should be made at an energy where a nucleon has been excited to a state lying off the mass shell.[1] Reaction (2) has long been known to have a peak in the total cross section at a gamma-ray laboratory energy $k_\gamma\approx 300$ MeV.[3] Since this peak is generally ascribed to the influence of the $\Delta(1236)$ in an intermediate state, a study of Reaction (1) at an equivalent neutron energy $T_n=2k_\gamma=600$ MeV appeared worthwhile. We communicated our interest in this reaction to Barshay who was independently studying reciprocity relations. Using a specific model he then suggested that the effects of time-reversal violation are important only for neutron energies near 600 MeV.[4] There, the predicted difference between the angular distributions of Reactions (1) and (2) is symmetric about 90° and could be as great as 40%. The total cross sections are predicted to be insensitive to time-reversal-invariance violation.

Our study of $n+p\to d+\gamma$ at these energies was complicated by the presence of the kinematically similar reaction

$$n+p\to d+\pi^0,\quad \pi^0\to 2\gamma. \quad (3)$$

The cross section for this process rises sharply from zero at the threshold of 275 MeV to a broad peak of 1.5 mb at a neutron energy of 600 MeV. This peak is roughly 70 times higher than that expected for $n+p\to d+\gamma$.

In this experiment, neutrons were produced from an internal Pt target at the Princeton-Pennsylvania Accelerator (PPA). A beam of approximately 5000 neutrons/sec was defined at an angle of 34° relative to the circulating 3-GeV proton beam. A 2-in.-thick lead brick followed by a sweeping magnet eliminated $\gamma$ rays and charged particles. The beam illuminated a 3-in.-diam circle on a 4-in.-long liquid-hydrogen target placed 51 ft away from the Pt target. Since the internal proton beam of the PPA consists of bunches <1 nsec wide and 66 nsec apart, the energy of our neutrons could be determined by measuring the time elapsed between the production of the neutron at the internal target and the passage of a deuteron through a counter $D_1$ placed immediately after the hydrogen target.

All deuterons from Reaction (1) emerge from the target at laboratory angles less than 15° and with momenta between 450 and 1500 MeV/$c$. These were detected in a spark-chamber spectrometer (see Fig. 1). The momentum of the deuteron was measured by four 0.001-in. aluminum-foil spark chambers placed on either side of a magnet having a bending power of 12° for 1 GeV/$c$. Most of the dueteron flight path was in helium at atmospheric pressure to reduce multiple scattering. To separate deuterons from protons we recorded the time of flight of the charged particle between counters $D_1$ and $D_{2-4}$.

Photons were converted in three lead-plate spark-chamber arrays. Each of these arrays consisted of 12 gaps, had an active height of 18 in., and was approximately 3.0 radiation lengths thick. For each array, scintillation counters were placed before the first gap (anti counters), and after the fourth, eighth, and twelfth gaps (gamma counters). To trigger the chambers we required a coincidence between (a) a signal from $D_1$, (b) a prompt signal from any of the 18 gamma counters, (c) a delayed pulse from $D_{2-4}$, falling within a broad "deuteron gate," but (d) no signal from any anti counter.

The chambers were photographed by a single 35-mm camera placed effectively 40 ft above the apparatus. Side views of all chambers were provided by mirrors attached to the sides of the chambers at 45°. Each picture also recorded the times of flight of the deuteron and the neutron.

Approximately 1.7 million pictures were taken. Of these, 1.1 million were in a format suitable for measurement by an automatic flying spot digitizer and have now been scanned. Of the remainder, 160 000 pictures have been scanned manually. A picture was measured if it contained (a) one clearly recognizable charged-particle track in the deuteron chambers and (b) one or two gamma showers, each at least two gaps long. (Since the plate separating the last two gaps before a gamma counter was only $\frac{1}{16}$-in. Al, almost all gamma

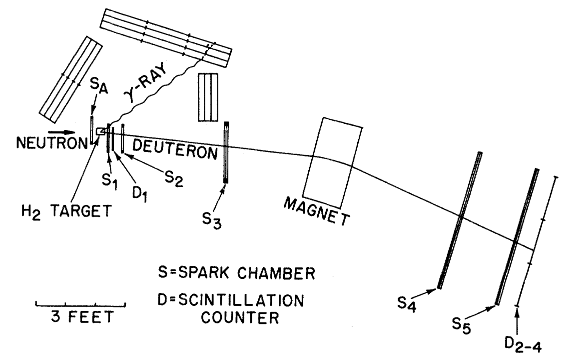


FIG. 1. Apparatus (top view). Counters $D_{2-4}$ are 18 in. high.

showers that triggered a gamma counter had at least two successive sparks.) A total of approximately 530 000 pictures were measured. Culled immediately from this sample were 27 000 events containing two gamma rays, 100 000 events having a spark in the thin chamber $S_A$ located upstream of the hydrogen target, and 25 000 events having a track beginning in the first gap of a gamma spark-chamber array. The sample was further depleted by discarding 60 000 events in which the charged particle leaving the hydrogen target was a proton rather than a deuteron. This separation could be made with better than 99.9% reliability. Then fiducial cuts were made in the location of the $\gamma$-ray conversion point so that a line from any point in the hydrogen target going to any point in the fiducial volume would pass through all three layers of gamma counters. This was done to facilitate calculation of the $\gamma$-ray efficiency. Similarly, events were rejected if the deuteron headed towards the gamma-chamber side of the beam.

About 100 000 events survived these cuts. Most of the events are examples of $n+p\rightarrow d+\pi^0$.[5] The main burden of the analysis is the extraction of 5000 examples of Reaction (1) from this dominant background. This extraction is accomplished in three basic steps. First, using the measured neutron and deuteron momenta for each event, we calculate the mass of the missing particle:

$$M_x^2(n,d)=(E_n+M_p-E_d)^2-(\vec{p}_n-\vec{p}_d)^2. \quad (4)$$

In principle, this calculation permits the separation of $n+p\rightarrow d+\gamma$ events ($M_x^2=0$) from $n+p\rightarrow d+\pi^0$ events ($M_x^2=M_\pi^2$). In practice, the two mass peaks overlap considerably owing to the poor resolution of the neutron momentum ($\Delta p/p=4\%$ at $T_n=600$ MeV). In the data to be presented, the ratio of the signal to background has been improved by retaining only events having $M_x^2(n,d) < 0.66 M_\pi^2$. Note that in this cut no information about the gamma ray is required. In the second step, the polar angle $\theta_{\gamma n}$ of the $\gamma$ ray plays the key role in the extraction of the signal. We assume that the energy of the neutron is unknown and use this angle to construct a neutron momentum

$$p_n' = p_d \frac{\sin(\theta_{dn} + \theta_{\gamma n})}{\sin\theta_{\gamma n}} \tag{5}$$

which would be the correct one for a $d\gamma$ event. A missing mass $M_x^2(\gamma, d)$ is now calculated using Eq. (4). Since $\theta_{\gamma n}$ is determined by the conversion point of the $\gamma$ ray and the intersection of the deuteron trajectory with a plane perpendicular to the neutron beam and through the center of the target, the length of the target contributes the largest error to $M_x^2(\gamma, d)$. Therefore, the dispersion of $M_x^2(\gamma, d)$ about zero is well understood and a cut in this quantity may be made reliably. Events having $|M_x^2(\gamma, d)| < 0.55 M_\pi^2$ were selected for the final step of the analysis.

The photon from Reaction (1) is coplanar with the neutron and deuteron whereas photons from Reaction (3) are in general not coplanar. To measure the coplanarity, a plane is defined by the gamma conversion point, the spark of the deuteron in gap $S_1$, and the center of the Pt target. "Coplanarity" is then the distance in millimeters of the deuteron spark in chamber $S_3$ from this plane. Before plotting the coplanarity of the events retained by the two mass cuts, we classified them into bins by their neutron energies (four intervals of 120 MeV) and deuteron c.m. angle defined as the supplement of $\theta_{\gamma n}^*$ (seven intervals of 20°). Figure 2 shows the coplanarity of events occurring in nine such bins. The shapes of both signal and background are well understood. At energies below the $d\pi^0$ threshold, the width of the $d\gamma$ signal is almost entirely due to multiple scattering of the deuteron. At higher energies, the width decreases somewhat and becomes dominated by measuring errors. At all energies above the $d\pi^0$ threshold, more than 98% of the $d\gamma$ signal is confined to coplanarities smaller than 20 mm. An exhaustive Monte Carlo simulation of the background reaction $n+p \to d+\pi^0$ shows that the background falls slowly as the coplanarity increases from 0 to 40 mm. Based on the number of events observed with coplanarity between 20 and 40 mm, the Monte Carlo program predicts the number of background events to be expected between 0 and 20 mm. The number of

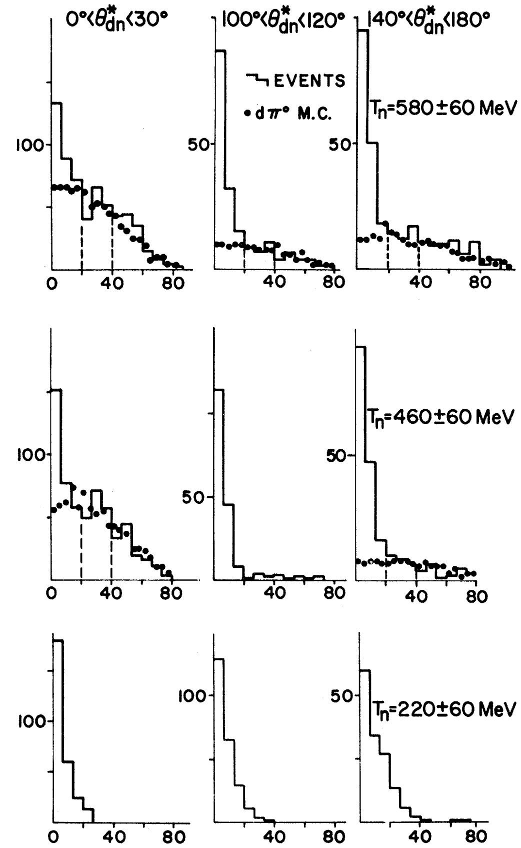


FIG. 2. "Coplanarity" (in mm) of events in three angular intervals.

$d\gamma$ events is then determined by subtracting this predicted background from the number of events actually observed between 0 and 20 mm.

A similar Monte Carlo simulation of Reaction (1) was used to calculate the efficiency of the apparatus as a function of angle and neutron energy. Included in this program were the efficiency for the detection of $\gamma$ rays as a function of their energy and their angle with the spark-chamber plates,[6] and the shape of the incident-neutron spectrum.[7] The program predicted the detection efficiency allowing for the number of valid $d\gamma$ events lost in the two mass cuts. By dividing the number of $d\gamma$ events in a given bin by the efficiency for that bin, we obtained four unnormalized angular distributions, one for each energy interval. Each of these distributions was then fitted by a third-order expansion, $A + B\cos\theta + C\cos^2\theta + D\cos^3\theta$, and normalized by requiring that the mean value of the fitted angular distribution (averaged over $\cos\theta$) be 1. The measurements by others of the differential cross section for $\gamma + d \to n + p$ have been converted to angular distributions by the

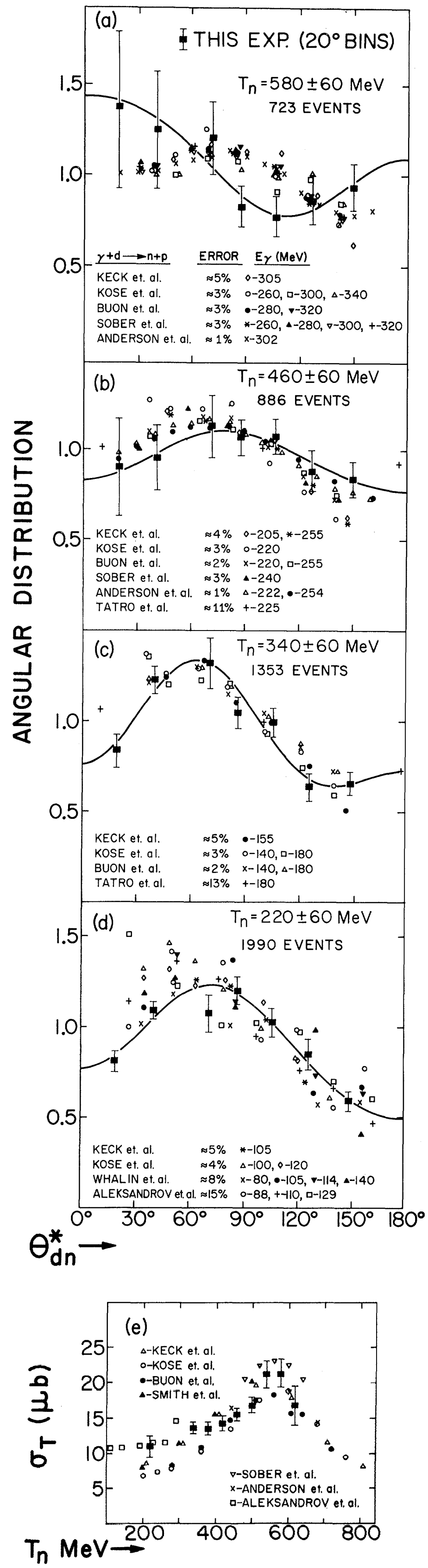


FIG. 3. (a)-(d) Angular distributions for $n+p \leftrightarrow d+\gamma$. The curves are third-degree polynomial fits in $\cos\theta$ to our data. (e) Our total cross sections for $n+p \rightarrow d+\gamma$, compared with those inferred from $\gamma+d \rightarrow n+p$ using reciprocity. For $\gamma+d \rightarrow n+p$ experiments, see Ref. 3.

same normalization procedure. Figures 3(a)-3(d) show a comparison of the angular distributions for Reactions (1) and (2). Our angular distributions agree well with those of the photodisintegration reaction for the three lower energy intervals, but do not agree as well at the neutron energy of 580 ± 60 MeV. For this energy, we notice that our angular distribution tends to be depressed around 90°, whereas that of the inverse reaction has a bump. Specifically, we find that $C/A = +0.5 \pm 0.3$ compared with $-0.22 \pm 0.02$ for the inverse reaction as measured by Anderson et al. (see Ref. 3). We have also made a direct comparison of our data points to the fit to their data. If the relative normalization is varied to minimize the $\chi^2$, we find $\chi^2 = 10$ for six degrees of freedom. The errors in our data points are purely statistical. We believe that the systematic uncertainties are small compared with these errors.[8]

We have also measured the total cross section for $n+p \rightarrow d+\gamma$ by normalizing to $\sigma(n+p \rightarrow d+\pi^0)$, assumed to be $\frac{1}{2}\sigma(p+p \rightarrow d+\pi^+)$ by charge independence. The results, which are presented in Fig. 3(e), are in good agreement with the inverse reaction at all energies, suggesting no effect of $T$ nonconservation in the total cross section.

Preliminary results from another measurement of Reaction (1) have already been reported[9] and further experiments are underway, here and elsewhere.

We wish to thank Michael Gruters for his untiring efforts in the development and operation of our automatic film scanner and David C. Cheng for joining us in measuring the polarization of the neutron beam. We have benefited greatly from the zeal of Professor Milton White and the staff of the Princeton-Pennsylvania Accelerator as well as from the advice of Professor S. Barshay and Professor S. Treiman. We thank the Cornell-Ithaca-Princeton and the Stanford Linear Accelerator Center–Stanford University groups for valuable discussions. Finally, we are indebted to our scanners and the Elementary Particles Laboratory Staff for their continuous assistance.

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[8]A possible source of systematic error could arise if the neutron beam were polarized. Reciprocity requires that the angular distributions for Reactions (1) and (2) be the same if initial-state spins are averaged and final-state spins summed. We have measured the polarization of the incident neutrons in our beam and found it to be $0.04\pm0.02$ ($T_n\approx 600$ MeV), a value too small to yield significant asymmetries. Our detector is insensitive to the spin of either the deuteron or the photon. A parallel situation holds for the measurement of Reaction (2).

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# CONNECTION BETWEEN $F_\pi(t)$ AND THE AMPLITUDES FOR $\pi\pi\to\pi\pi$ AND $\pi\pi\to\pi A_1$ *

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The current-algebra connection between the pion electromagnetic form factor $F_\pi(t)$ and the amplitudes for $\pi\pi\to\pi\pi$ and $\pi\pi\to\pi A_1$ is examined by explicitly extrapolating off the pion mass shell the matrix element $\langle\pi|A_\mu|\pi\pi\rangle$ which is taken to be dominated by $\pi$ and $A_1$ poles and possible subtractions. It is found that the connection is broken by the presence of an almost arbitrary subtraction function. In particular the $A\rho\pi$ interaction remains arbitrary as well as the form for $F_\pi(t)$. The results are applied briefly to the Veneziano model.

Several authors[1] have recently explored the connection between the amplitudes $\pi\pi\to\pi\pi$ and $\pi\pi\to\pi A_1$ that follows from the assumptions that the matrix element $\langle\pi\pi|A_\mu|\pi\rangle$ is dominated by $\pi$ and $A_1$ poles and that the scattering amplitudes are given by the Veneziano model.[2] Oyanagi[3] has extended the analysis by extrapolating to zero the momentum of one of the pions in the matrix element and thereby obtaining a Veneziano-like expression for $F_\pi(t)$. One result of this work, and that of a subsequent analysis,[4] has been to propose a vanishing $D$-wave $A\rho\pi$ interaction, either to yield a more convergent $F_\pi(t)$ for large $t$ or to eliminate satellites from the $\pi\pi\to\pi\pi$ and $\pi\pi\to\pi A_1$ scattering amplitudes. In all these treatments, however, the extrapolation of one pion off the mass shell of the amplitude $\langle\pi\pi|A_\mu|\pi\rangle$ has not been done in a consistent way.[5] We intend to summarize the results of such a consistent treatment in this Letter and show that the use of the Veneziano model for this example imposes no restriction on the $D$-wave $A\rho\pi$ interaction and that one is free to obtain almost any asymptotic behavior for $F_\pi(t)$.

Consider the amplitude for $\pi^+(p)+\pi^-(q)\to A_\mu{}^+(k)+\pi^-(q')$ with the $\pi^+$ extrapolated off the mass shell,

$$M_\mu=\tfrac{1}{2}\int dx\, e^{-ipx}\langle\pi^-(q')|T[\partial^\lambda A_\lambda{}^+(x),A_\mu{}^-(0)]|\pi^-(q)\rangle. \quad (1)$$

Here $k+q'=p+q$ and $px=p^\lambda x_\lambda=p_0x_0-\vec{p}\cdot\vec{x}$. We take the conventional current-algebra commutation